NEUTRAL DENSITY MEASUREMENTS IN AN NH_3 MPD ARC

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for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

1. INTRODUCTION

1.1 Program Objectives

The program described in this report was to determine experimentally the range of applicability of a vacuum ultraviolet absorption spectrometry technique to detecting neutral atom and molecule constituents in the exhaust stream of an MPD arc jet. Specifically, emphasis was on measuring the nitrogen atom densities in an ammonia-fueled MPD arc jet exhaust. To date, no other techniques have been established for measuring this quantity, possibly important for the corroboration of arc jet propulsion efficiency figures obtained from thrust and input mass flow measurements. An analysis is presented for the reduction of transmissivity data in terms of nitrogen atom flow rates. The main purpose of this program was to establish the experimental technique for this new application; more systematic use of this technique to help determine the operating characteristics of the NH_3 MPD arc would be undertaken in subsequent programs.

1.2 Background

An examination of the papers given at the last few AIAA Electric Propulsion Sessions (Colorado Springs, September 1967; New York, January 1969; and Williamsburg, March 1969) reveals that much remains to be done in order to have a comfortable understanding of the manner in which an MPD arc thruster operates. A number of workers[1-3] have indicated that at least for the NH_3 arc a significant number of neutrals must be present in the exhaust in order to account for the fact that thrust efficiency ($T^2/2\dot{m}P$)

is comparable to the limit imposed by frozen flow considerations, making the assumption of 100% dissociation and ionization. Yet, a very limited knowledge of the state of the neutrals in the exhaust stream is available.

In any event, past experience has indicated that no single group of measurements, such as thrust and input mass flow, should be entirely relied upon to determine the performance of an electric thruster. Exhaust stream diagnostics would provide an excellent source of data for correlating with thrust and input mass flow measurements provided that all of the high velocity particles in the stream are properly accounted for. Specifically, the exhaust stream measurements of interest for this purpose are species identification (mass per particle), particle number densities, and velocity distribution. Data from these measurements may be combined to determine ρAv^2 which may be compared directly with the measured thrust. To date, only a partial accounting by these techniques has been attempted. The issue is complicated by the fact that the exhaust stream probably consists of many different species, e.g., for the NH_3 arc, both the ground and excited states of N, N^+, NH_3, H, H_2, H_2^+, H^+ and NH. In principle, velocity data for the luminous species may be obtained spectroscopically by Doppler shift measurements[1,4,5]. Such measurements have been reported[1,4] for the NH_3 arc, but only for the N, N^+, and H components so far.[6] Direct measurements of neutral densities are completely absent at this point. The nitrogen atom was chosen as the subject for these initial experiments since it was

thought to be one of the important constituents in the exhaust. The vacuum ultraviolet (VUV) spectroscopic absorption technique had been previously developed for xenon[8,9] at 1470 Å so that adaptation to detection of nitrogen at 1200 Å was a relatively minor part of this program.

2. EXPERIMENTAL

2.1 Vacuum Test Chamber

The vacuum chamber used in this program has been described in detail elsewhere.[10] Briefly, it consists of a 3 ft. diameter, 13 ft. long stainless steel chamber with a shorter, larger diameter addendum normally used to house a thrust balance for plasma engine tests. The long tank is pumped, in turn, by three CVC MC-28000 oil diffusion pumps, a CVS KS-2000 diffusion ejector, and a mechanical pump rated at 200 cfm. This system is illustrated in Figures 1 and 2.

The test chamber was divided into two parts with a water-cooled baffle plate about 22 cm from the arc. A 20 cm diameter hole was cut in the center of the baffle to restrict the exhaust beam to less than 20° spreading half-angle. Most of the gas intercepted by the baffle was pumped by one of the three diffusion pumps; most of that transmitted was pumped by the other two diffusion pumps.

2.2 The Measuring System

A Jarrell-Ash one-meter normal incidence concave grating vacuum spectrometer was used for these studies. This spectrometer can be used both as a scanning monochromator and a photographic spectrometer. It employs a diffraction grating with an optical surface optimized for the

spectral region above 1100 Å. The detector consists of an especially selected RCA type 7265 photomultiplier which is placed behind a thin Pyrex vacuum window coated with sodium salicylate. This particular detector combination was found to be far superior to a number of other detectors attempted in this particular wavelength region, including a Bendix windowless photon detector and an EMI windowless photon detector. The need for a solar-blind detector was obviated by the superior quality of the grating, which had a low degree of scattered light. The photomultiplier is read either directly on an oscilloscope or on a strip chart recorder after appropriate amplification.

Referring to Figure 1, the 1-meter normal incidence JACO-Hilger vacuum ultraviolet spectrometer is optically connected to the observation chamber by a windowless vacuum-tight pipe fitted with a gate valve and bellows for ease in connecting and disconnecting the spectrometer. On the opposite side of the observation chamber is shown the mirror mount also provided with a gate valve to permit convenient removal for cleaning. The manipulator, also shown in Figure 1, permits focusing, rotating, and tilting of the mirror so that a good image may be obtained at the entrance slit of the spectrometer while the entire system is under a vacuum. The mirror was aluminized and overcoated with MgF_2.

The light source used in these studies consists of an air-cooled quartz capillary through which nitrogen flowed. A 250 micron slit was placed at the vacuum chamber end of this tube to permit higher

operating pressures in the tube than are maintained in the vacuum test chamber. Excitation is achieved in a tuned cavity driven by a 2.145 KMC, 125 watt, oscillator.

2.3 Power Supplies

The power supply used to run the arc was originally capable of supplying 600 amps and an open circuit voltage of 95 volts. It was found necessary to modify this supply to provide an open circuit voltage of about 180 volts, at the expense of current rating, in order to permit consistent operation of the arc in ammonia. A combination of variable transformers and a saturable core reactor were used in the primary circuit to control the operating current of the arc. The control characteristics of the reactor are shown in Figure 3.

As will be discussed further, it was found convenient to provide an additional anode external to the arc proper in order to start the arc consistently. The power supply used for this purpose provided 2000 volts dc at 10 amps through a ballast resistor of 200 ohms. This power supply was floating and connected to the main power supply at the common cathode.

The power supply used to provide the magnetic field delivered 330 amps at 45 vdc.

2.4 Arc Details

The arc was constructed according to plans supplied by Langley Research Center and is identical with one of the configurations used in a number of experiments[1,4] at LRC. In Figure 4 is shown the cathode assembly. The

cathode tip was obtained from Semicon Associates and was manufactured from their F-Cathode Material, Serial # 5-84-4; 1; 1. (bariated tungsten). The water-cooled tungsten tip holder is surrounded by a pyrolitic boron nitrode shroud. Propellant was fed through the holes shown in the shroud into the anode plenum chamber. The anode assembly is shown in Figure 5, with the cathode assembly in place. The large boron nitride nozzle at the orifice serves to localize anode attachment to the inside of the anode assembly, i.e., in the plenum. Not shown in the figures is the water-cooled second anode (for starting) which was located adjacent to the anode shroud. This consisted simply of a 1/4 inch thick copper disc with copper tubing attached and with a hole to match the i.d. of the outer part of the boron nitride nozzle (2-1/4").

The entire arc assembly is shown in Figure 6, including the water-cooled coils used to supply the magnetic field, normally 5000 gauss on the axis of the coils. This entire assembly was placed in the vacuum chamber during the tests. The main arc power was brought into the vacuum chamber on the copper water inlet and outlet tubes, which, in turn, were brought through the chamber walls in nylon compression fittings. Nylon tubing was used at the arc to isolate the power leads from the common water supply system for both electrodes. The ammonia flow rate was controlled by a needle valve and measured by a tapered capillary-flow ball tube calibrated for ammonia.

3. SHAKEDOWN TESTS

3.1 Operation of the Arc

A rather extensive program was required in order to obtain stable operation of the arc in ammonia. The most important factor in these difficulties was that the no-load available dc voltage from the supply (95 volts) was apparently insufficient for long-term stable operation of the arc in ammonia. The attempts at operating under these conditions were prolonged by the incentive obtained from initial successes along these lines, presumably as a result of using a fresh bariated tungsten cathode tip. Stable operation in argon was always possible, however, once the start-up procedure had been perfected. A number of arc initiating schemes of increasing complexity were tried. Low-energy, high voltage schemes were found to be inadequate. The technique finally settled upon consisted of adding a second water-cooled starter anode adjacent to the boron nitride nozzle and with the same size opening as the downstream end of a nozzle. Thus, to start, a 10 amp, 2000 volt supply in series with an air-cooled 200 ohm resistor bank was used to draw an arc between the second anode and the common cathode with the B-field turned off. This readily permitted start-up in argon with the main power supply, subsequent application of the B-field, and shut-down of the starter anode, but the arc extinguished when the flow was switched to ammonia.

The arc power supply was modified to almost double the voltage at the expense of current capability, now 350 amperes maximum. This permitted a smooth transition from argon to ammonia flow and long-term

stable operation in ammonia. Start-up directly in ammonia was still not possible with the present arrangement, so the procedure of starting in argon, heating the cathode, and switching over to ammonia flow was continued.

Other difficulties occurring during the shakedown runs included disasters with arc-over between the uninsulated water-cooled power leads and rapid deterioration of the collimating mirror used in the absorption apparatus. The former difficulty was reduced by wrapping the leads with polyethylene tape. The latter was reduced by providing a shroud and movable cover to protect the mirror surface from the products of the arc except for the short periods required for the measurements, along with frequent recoating of the mirror. In one case, the reflectivity of the mirror was found to decay to 10% of its original value during a 20 minute exposure to the arc products.

3.2 Operation of the Light Source and Spectrometer

The background light source produced a 1200 Å nitrogen atom line received in the spectrometer, reflected from a freshly coated mirror, some 15 times brighter than that received directly from the arc in ammonia; thus, meaningful absorption measurements were readily accomplished.

During the period of construction of the arc, some experiments were performed with the light source alone in order to explore the spectral characteristics of the source. A spectral range of 800-3000 Å was covered.

The required N I 1200 Å lines were the strongest radiators in this spectral range. Five other N I lines of comparable intensity were also generated in this wavelength region. Other features of the spectrum included the observation of several bands of the Lyman-Birge-Hopfield system of N_2 with sufficient intensity for absorption measurements, part of the Second Positive system with even higher intensity, a strong Lyman-alpha line of hydrogen at 1215 Å, and, finally, weak lines and continuum extending down to 800 Å.

Records were obtained also while flowing ammonia and hydrogen through the discharge. In terms of the atomic lines observed, there was relatively little difference in both these cases when compared to the runs using nitrogen, possibly due to a slight leak which developed during operation of the source. However, molecular bands of nitrogen were replaced by molecular bands of hydrogen when hydrogen was used in discharge. When ammonia was used, no recognizable molecular bands appeared other than those for nitrogen.

3.3 Arc Emission

In view of the uninteresting spectrum resulting from flowing ammonia through the background light source and the difficulties encountered in operation of the arc, it was deemed advisable to avoid any extensive mapping of the arc emission spectrum in the vacuum ultraviolet. In the course of obtaining the absorption data, however, it was noted that the Lyman-alpha line of hydrogen at 1215 Å was about five times brighter than the nitrogen atom line at 1200 Å. This does not preclude the possibility of measuring

the absorption of hydrogen, however, since it may be possible to generate a background source line at 1215 Å that is still brighter by flowing hydrogen or perhaps even ammonia through the discharge lamp. This possibility remains to be tested.

Probably also worth mentioning are some observations made during a period of time when the vacuum system was not operating properly, due to malfunction of some of the diffusion pump heaters, and the background pressure during operation was in the 10^{-3} mm range. Under these conditions, the hydrogen emission line at 1215 Å was more than ten times as bright as the nitrogen lines at 1200 Å, the absorption of the cold ammonia was an order of magnitude higher than shown in Figure 7, and the transmissivity of the arc plume at 1200 Å was 3-10 times lower than shown in Figure 7.

4. ABSORPTION MEASUREMENTS

Absorption measurements were made at a downstream position in the arc plume about 52 cm from the external nozzle (see Figure 8). The flow range covered was from 6 - 18 mg/second. The arc was operated at 300 amperes and 63 - 80 volts dc, depending on the flow rate. The magnetic field was maintained at 5000 gauss for all of the runs. Observed transmissivity (I/I_o) of the arc under these conditions is indicated in Figure 7, along with similar data for the cold ammonia flow with the arc power turned off. It will be noted that the transmissivity follows a smooth downward trend within $\pm$ 10% as ammonia flow rate increases. The cold flow ammonia absorption at 1200 Å is sufficiently small so that it can be neglected, within

the accuracy of these experiments. This approximation is improved as the degree of dissociation of the ammonia by the arc increases. It has been hypothesized that the small amount of 1200 Å absorption observed in the cold ammonia flow is due to the production of nitrogen atoms in the photo-dissociation of the ammonia by the VUV energy from the light source at other wavelengths.

The background pressures during these runs, as indicated by a hot filament ionization gauge, are shown also in Figure 7. It should be kept in mind that the gauge had been calibrated for air rather than ammonia, in which these readings were taken. It was noted that these readings did not change significantly during operation of the arc at a given flow rate. It should be mentioned again that some earlier runs, taken at about an order of magnitude higher background pressures (prior to repair of the pumping system) resulted in considerably higher absorptions for both the cold ammonia and the arc plume flow.

5. ANALYSIS AND RESULTS

5.1 Nitrogen Atom Densities

The transmittance at any point in the spectral line is given by

$$I(\nu) / I_o(\nu) = e^{-k(\nu) n L} \qquad (1)$$

where n is the number density of absorbers and L is the total absorbing path. Under the conditions of the present experiment, the background emission line is much narrower than the absorption line in the arc plume,

principally because of the symmetrical Doppler broadening due to the arc plume spreading. Therefore, the only useful part of the absorption coefficient, k (ν), is at the line center, which we shall call k_o. Thus, one can immediately write the expression for the integrated absorption as

$$I/I_o = e^{-k_o nL} \tag{2}$$

Solving for the unknown,

$$n = (1/k_o L) \ln (I_o/I) \tag{3}$$

where, for a Doppler-broadened line,

$$k_o = \pi^{1/2} r_e \, cf \lambda_o / \bar{v} \tan \alpha$$

and $r_e = 2.82 \times 10^{-13}$ cm

$c = 3 \times 10^{10}$ cm/sec

f = 0.35 (Sum of the multiplet component oscillator strengths; accuracy $\pm$ 50% --- See NBS Publication #NSRDS-NBS 4)

$\lambda_o = 1200$ Å

α = half angle of spreading in the exhaust plume

$\bar{v}$ = average axial velocity of the absorbing species in the plume

The total rate of flow of the absorbing species is given by

$$\dot{N} = nA\bar{v} = (\pi^{1/2}/16 \, r_e \, cf\lambda_o) \bar{v}^2 L \tan \alpha \ln (I_o/I) \tag{4}$$

where the radius of the cross-sectional area A has been taken as L/4 (See Figure 8). The value of the fixed constant within the brackets is 3.11×10^6 sec cm^{-3}. L is the sum of the two lengths A and B shown in

Figure 8. The half angle was taken to be 20^{o}, as defined by the arc position and baffle aperture. It should be noted, however, that the visual appearance of the arc plume was indicative possibly of a somewhat smaller angle. Based on Kogeschatz's results[4] from his Doppler shift measurements, $\bar{v}$ for the nitrogen atom is taken to be 3×10^{5} cm/second over the operating range covered here. Two things should be noted in this regard. First, the range of operating conditions in these experiments extended to lower flow rates than those of Kogelschatz; it is assumed that the constancy of the velocity noted by him extends also to the lower flow rates. Second, Kogelschatz's observations involves the luminous nitrogen atoms 9.5 cm downstream from the anode face whereas these experiments involve the ground state atoms 52 cm downstream. In view of the short radiative lifetime of the atomic states, it is assumed that the excited atoms observed by him resulted from re-excitation in the exhaust plume as a consequence of the extended currents from the arc. It therefore seems reasonable to assume that the excited and ground state atoms are moving with the same average velocity.

However, since he also observed ion velocity increasing downstream from the 9.5 cm point, the assumption of constancy of neutral atom velocity from the 9.5 cm to the 52 cm point is not completely satisfactory. In fact, it is more probable that the nitrogen atom velocity increases at points further downstream as a result of collisions with the faster ions. Unfortunately, the rate of increase is not known, so we will choose the one value available to us.

It should be noted that nitrogen atom axial velocities six times greater than this have been observed at Lewis Research Center in a 30 KW radiation-cooled NH_3 arc plume[6] under comparable conditions of current and flow. It should be emphasized, however, that the discharge chamber design and magnetic field shape and strength were different in the two cases. While such a large difference in the measured velocities is surprising even with the geometry differences involved, we must choose to rely on Kogelschatz's results since his experiments were performed with the same arc geometry and background pressures used here.

Using the data and assumptions of the preceding paragraph, Equation (4) can be evaluated for a number of different operating conditions. The results are shown in Figure 9. It can be seen that maximum fractional amount of ammonia observed in the plume was about 1.5% and that this fraction is almost independent of flow rate. Additional assumptions used in reducing the data are: (1) The ammonia has been completely dissociated in the arc. Therefore, the cold ammonia absorption indicated in Figure 7 can be disregarded. (Assuming α and L to be the same for the cold ammonia, and that its velocity is an order of magnitude lower than the arc products, the observed transmissivities represent fractional dissociations of the order of only 10^{-4}.) (2) The quantity I is obtained by subtracting from the intensity of the background source as seen through the arc plume, the weaker intensity of the arc by itself. The absolute accuracy of these results is no better than the $\pm$ 50% quoted for the oscillator strength, f, and depends also heavily on the assumed applicability of the value used for $\bar{v}$.

5.2 Hydrogen Atom Densities

By making a number of assumptions, it is possible to obtain a rough estimate of the hydrogen atom component in the arc plume by comparing the emission intensity of the H I 1215 Å line with that of the 1200 Å lines of nitrogen. The oscillator strengths for the two species are quite comparable. The assumptions required are that the excitation mechanism (assumed to be arc currents extended into the flow) is the same for both, that the two excitation cross-sections are comparable, and that the axial velocities are comparable. Based on these assumptions, there appear to be about five times as many hydrogen atoms present in the flow as nitrogen atoms. This, in turn, implies either incomplete dissociation of the ammonia molecule, or different fractional ionizations of nitrogen and hydrogen, or both. The presence of significant amounts of the NH radical would be supported by this result. On the other hand, if it is assumed that the velocities of the neutrals are inversely proportional to the square root of their masses, then the amounts of hydrogen and nitrogen atoms would be comparable.

6. CONCLUSIONS

While the main purpose of this program was to establish the applicability of a VUV absorption technique to determine the densities of various species in the exhaust plume of an MPD arc, some tentative information regarding the composition of the arc plume has been obtained also. The low percentage of nitrogen and hydrogen atoms indicated in the

exhaust plume would imply that these species are of little importance in determining the performance of the arc. Since the number densities reported depend on the square of the axial velocity of the particular specie (Equation 4), the accuracy of this parameter is especially important. Thus, if the velocity of the non-luminous nitrogen atoms were significantly higher than observed by Kogelschatz for the luminous ones, or if there is a significant increase in the velocity observed by him at the 9.5 cm downstream point when proceding further downstream to the 52 cm point used in these studies, the role of these constituents could be converted from minor to major.

As a recommendation for future investigation in this area, it would seem appropriate to apply a crossed-beam technique to the arc plume, i.e., an intense electron beam traversing the plume in order to excite the major non-luminous species. Thus, emission spectroscopy in the near ultraviolet and visible could be used to identify the species present. It may also be possible to extend the techniques of obtaining the velocities from the Doppler shift by use of such a crossed-beam approach. Finally, if a cross-calibration between the intensity of a species in crossed-beam region and the absorptivity of that same specie in the absence of the e-beam were made at one point in the arc plume, the e-beam could be used as a more convenient means for qualitatively mapping the density of non-luminous species at various points in the exhaust.

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FIGURES

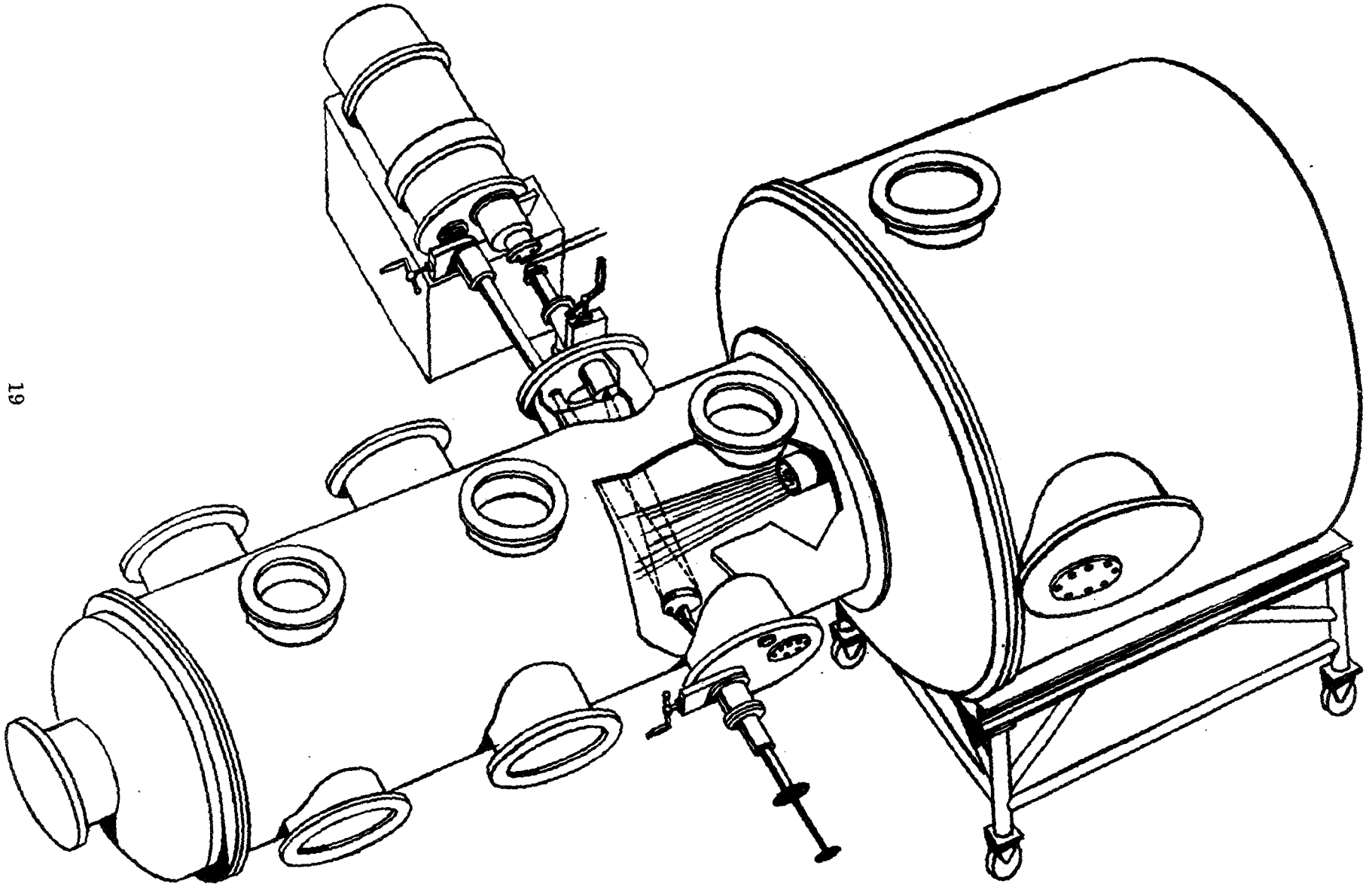
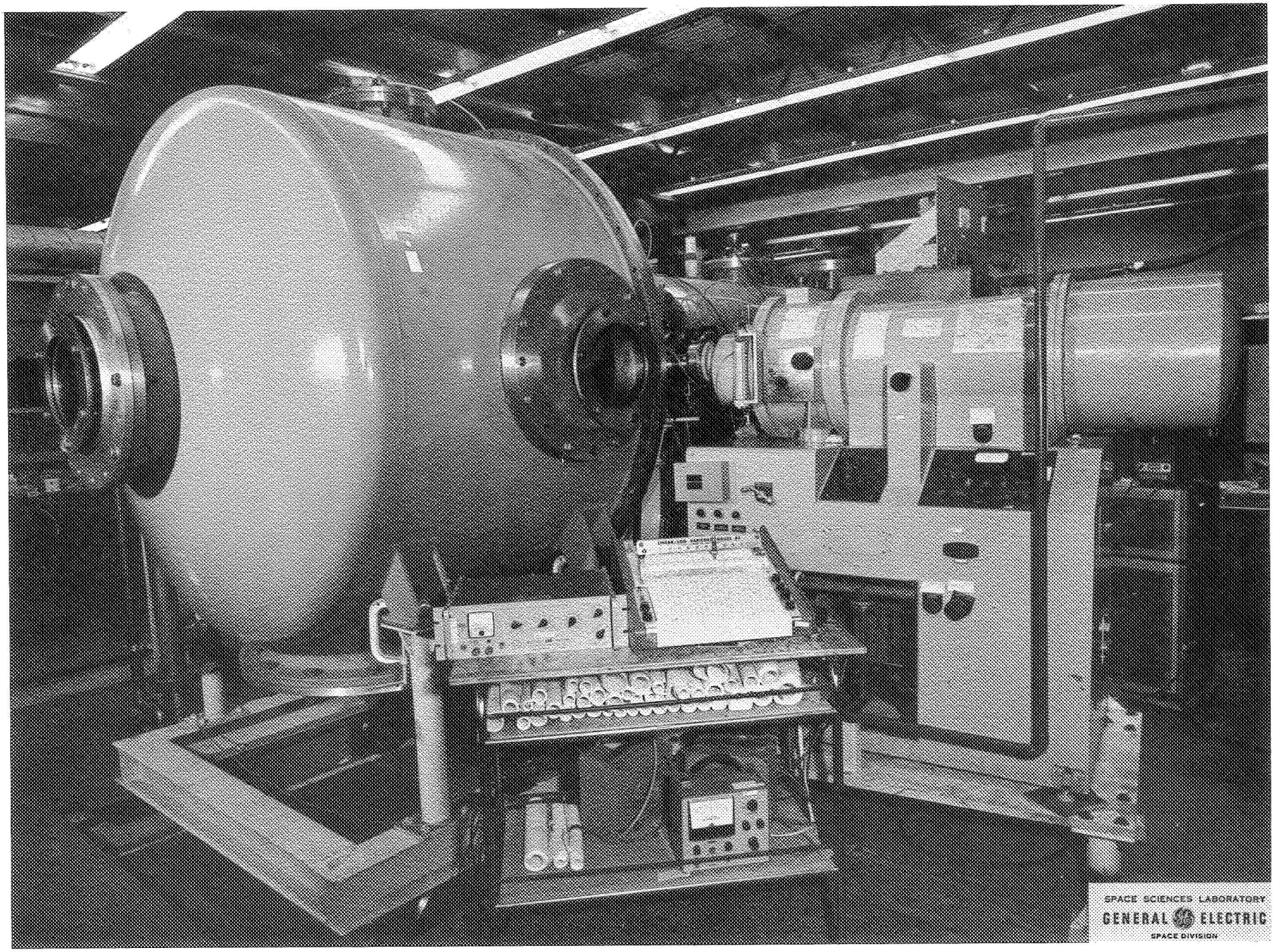


Figure 1. Optical Arrangement for Vacuum Ultraviolet Measurements.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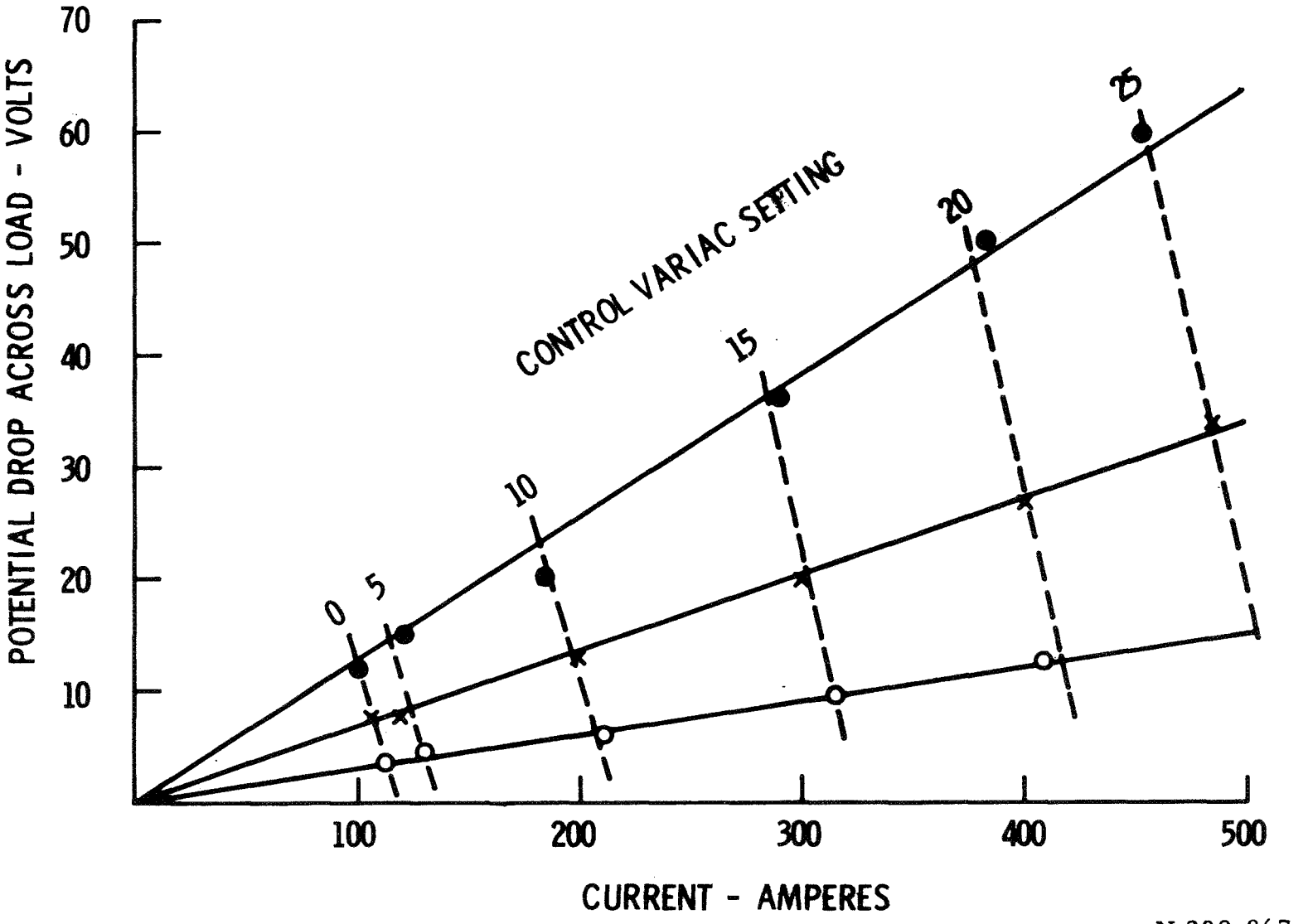

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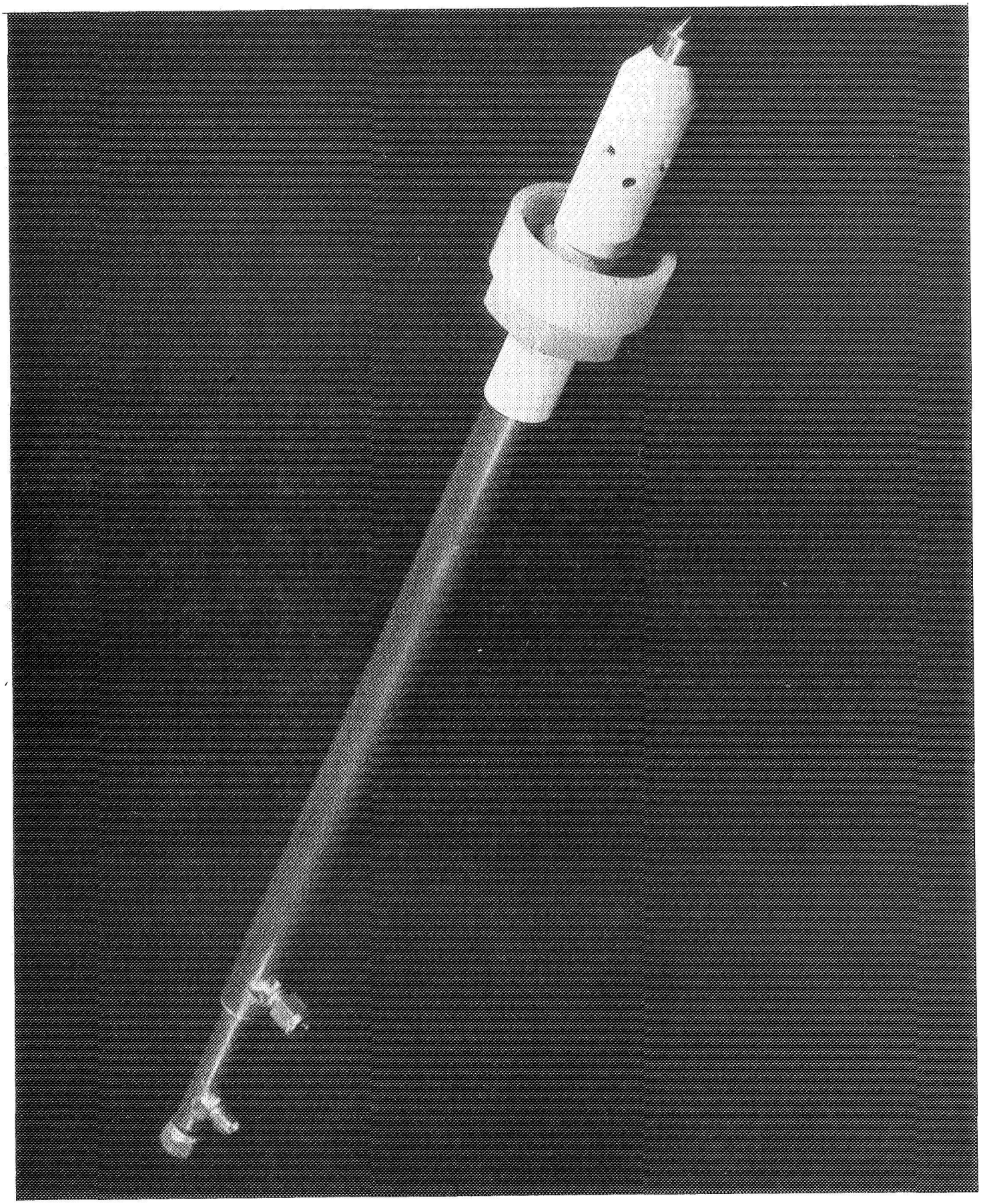
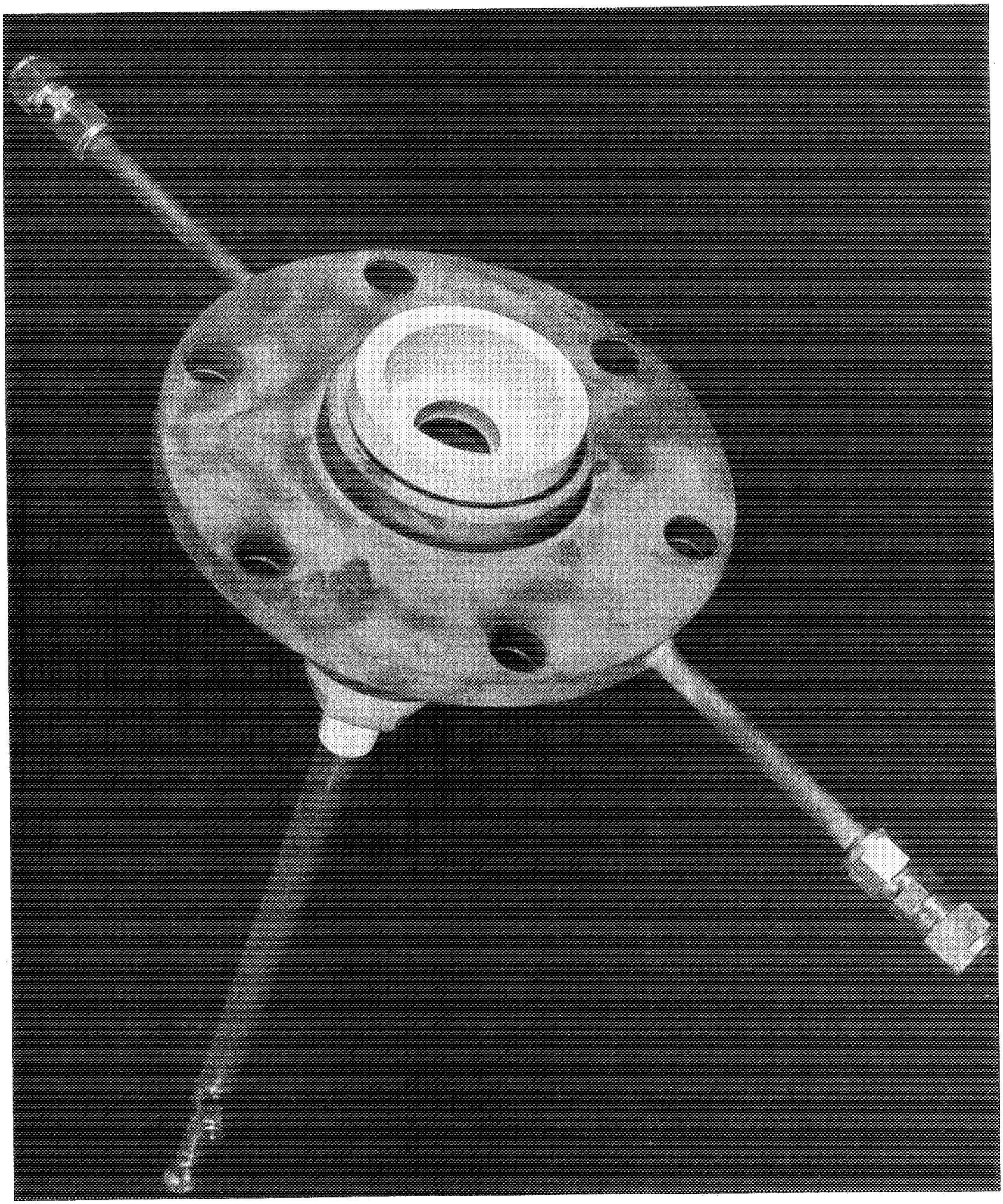
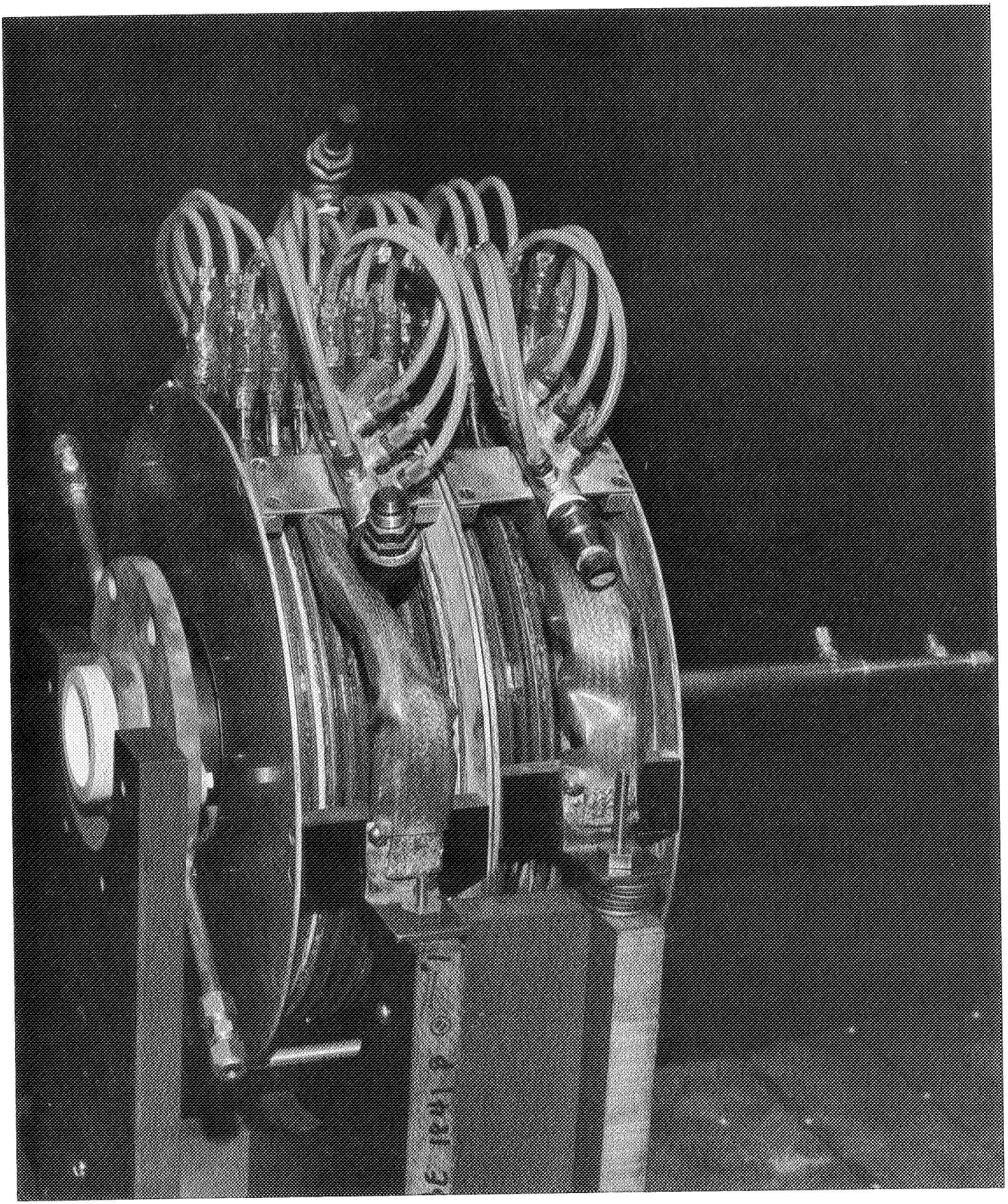
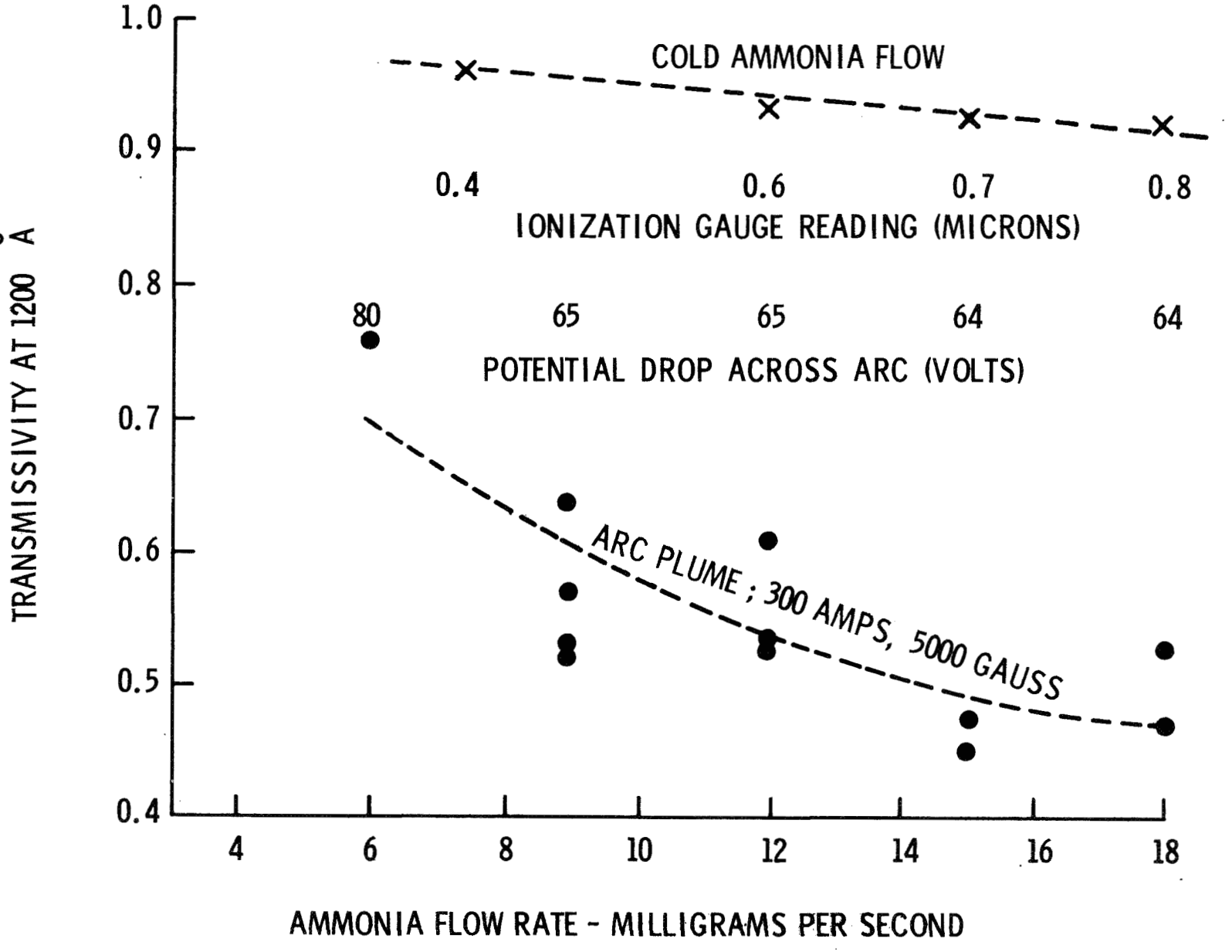
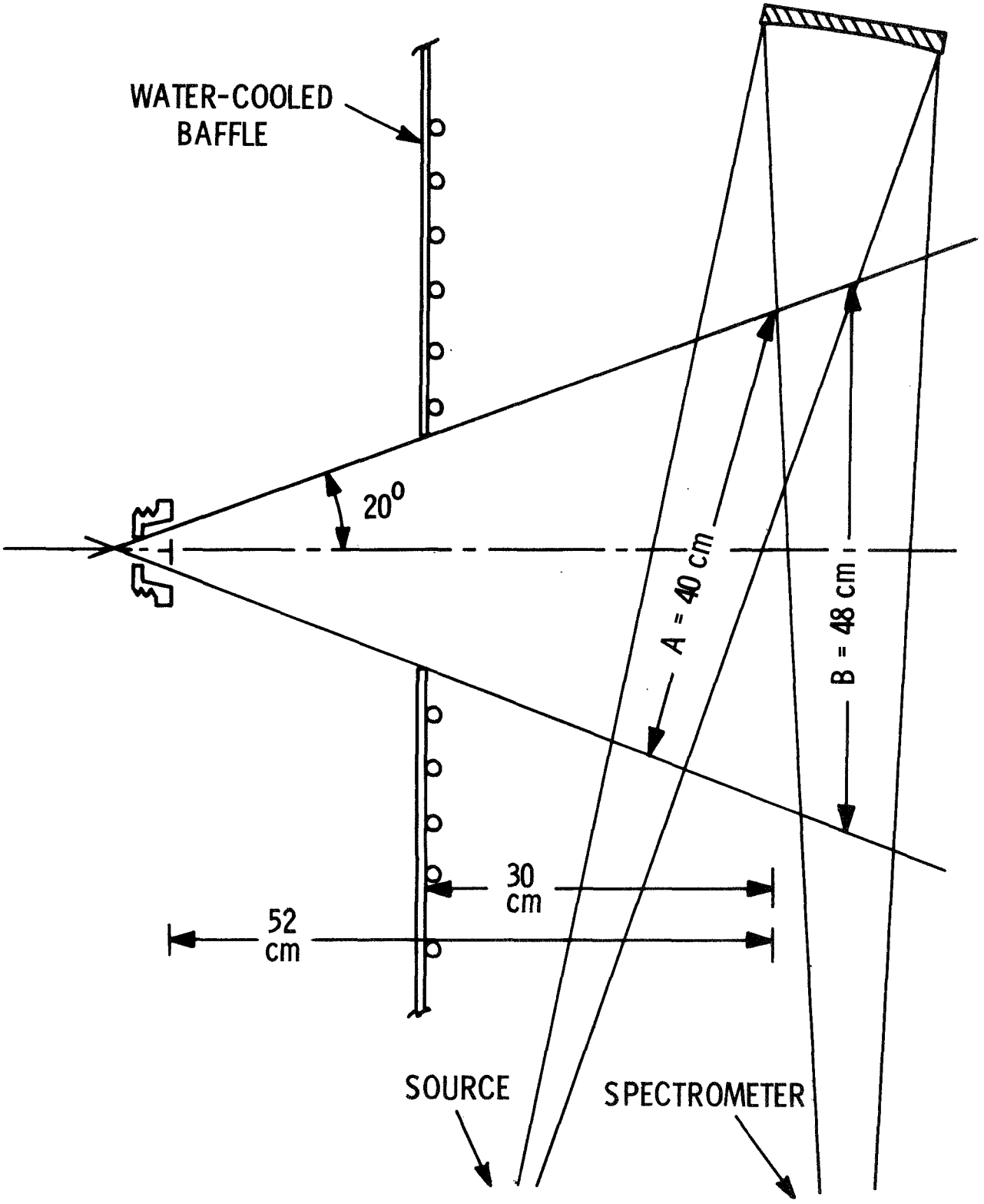







1.0
0.9
0.8
0.7
0.6
0.5
0.4
TRANSMISSIVITY AT 1200 Å
COLD AMMONIA FLOW
0.4
0.6
0.7
0.8
IONIZATION GAUGE READING (MICRONS)
80
65
65
64
64
POTENTIAL DROP ACROSS ARC (VOLTS)
ARC PLUME ; 300 AMPS, 5000 GAUSS
4
6
8
10
12
14
16
18
AMMONIA FLOW RATE - MILLIGRAMS PER SECOND


WATER-COOLED
BAFFLE
20°
A = 40 cm
B = 48 cm
30
cm
52
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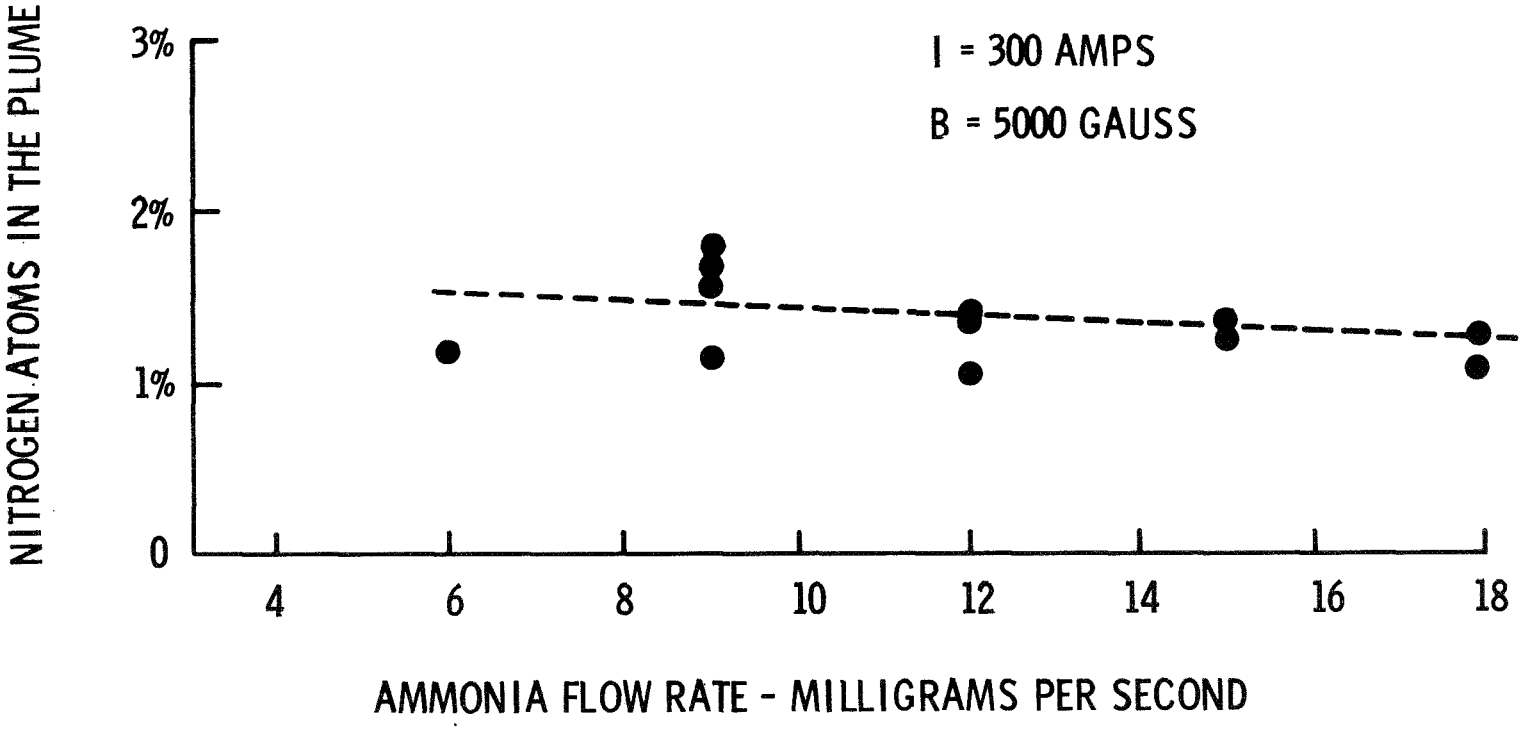
SOURCE
SPECTROMETER



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